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Final Report on grant DAAH04-96-1-0030
"Laser and Optical Physics"

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The following problems were studied under grant DAAH04-96-1-0030:

(1) Analytical solution of the photon (or elastic particle) transport problem;

(2) Inverse image reconstruction of objects in highly scattering media.

I. ANALYTICAL SOLUTION OF THE PHOTON (OR ELASTIC PARTICLE) TRANSPORT PROBLEM

Search for an analytical solution of the time-dependent elastic Boltzmann transport equation has lasted for decades. Beside being considered as a classic problem in fundamental research in statistical dynamics, a novel approach to an analytical solution of this equation may have applications in a broad variety of fields, such as light propagation in cloudy atmospheres and human tissue, particle diffusion in media, and so on. To our knowledge, an exact solution, even in an infinite uniform medium, is available only for isotropic scattering case, given by E. H. Hauge (1974), in the form of a Fourier transform in space and Laplace transform of the desired solution. Based on the angular moment expansion with cut-off to certain order, the Boltzmann transport equation is transformed to a series of moment equations. In the lowest order, a diffusion equation is derived and its analytical solution in an infinite uniform medium is obtained for anisotropic scattering cases. This analytical solution

has been broadly applied in many applications. For example, the solution of inverse problems in optical tomography, such as the location of a tumor in a women's breast from the scattering of light pulses, requires the inversion of a weight matrix obtained by convoluting two Green's functions of the forward scattering problem. The analytical solution of the diffusion equation has provided the Green's function in current use. A similar procedure can be applied to many other problems, such as using a laser to monitor cloud distributions, to detect objects inside or through cloud, or the use of low frequency sound to detect oil-bearing layers deep under water. However, the diffusion approximation fails at early times when the particle distribution is still highly anisotropic. The solutions of the diffusion equation or the telegrapher's equation do not produce the correct ballistic limit of particle propagation. Numerical approaches, including the Monte Carlo method, are the main tools in solving the elastic Boltzmann equation; however, detailed solution of a five-dimensional Boltzmann transport equation using a predominately numerical approach leads to prohibitive CPU times. To calculate the weight function and in the inverse process, we need an analytic approximation to the Green's function of the photon transport equation of simple enough form that the convolution of the Green's function and the inverse image reconstruction can be performed.

During the period of this project, we have developed an accurate analytical approach to solve the elastic Bolzemann transport equation in an infinite homogeneous scattering medium with an arbitrary form of the single differential scattering cross section (phase function). What has been accomplished is the following:

1. An exact solution of the angular Green's function (after integration over all positions) for an arbitrary phase function.

2. A cumulant approximation exact to second order over the spatial variables (for arbitrary

directions and time), that means the center position and half-width of the photon distribution are exact.

3. An analytic procedure for going to solutions exact to cumulants of arbitrarily high order. Note, however, that adding cumulants of higher order will have no effect on the lower order cumulants.

4. A generalization from a scalar Green's function to a dyadic which handles polarization effects of light described in terms of Mueller matrices.

These substantial accomplishments have direct applications in atmosphere physics, reconnaissance through clouds, monitoring in battle fields through dust, fog, and cloud, and breast cancer detection.

II. THREE DIMENSIONAL IMAGE RECONSTRUCTION IN TURBID MEDIA

Near-infrared optical imaging of the internal structure of biological tissues, such as a tumor in a breast, is an active area of contemporary photonic and biomedical research. we have developed inverse reconstruction algorithms and a time-sliced data acquisition approach that allow fast data acquisition and image reconstruction.

The algorithms use

(1) a 2D matrix inversion with 1D Fourier transform inversion based on the symmetry of cylindrical coordinates using a point source of light.

(2) a 1D matrix inversion with 2D Fourier transform inversion based on translation invariance using a plane uniform source of light.

These two methods greatly reduce the computation time compared to direct 3D inversion.

The data is collected in a transillumination geometry using an ultrafast electronic gate imaging system consisting of a gated image intensifier coupled to a charge-coupled device (CCD) camera. It provides a sequence of picosecond time-gated two-dimensional spatial intensity distributions at different times.

3D images of an absorbing object hidden inside a turbid medium are reconstructed using both simulated and real experimental data.

List of Publications

[1]W. Cai, B. B. Das, F. Liu, M. Zevallos, M. Lax, R. R. Alfano, ''Time Resolved Diffusion Tomographic Image Reconstruction in Highly Scattering Turbid Media'' in *OSA TOPS on Advances in Optical Imaging and Photon Migration,* edited by R. R. Alfano and James G. Fujimoto, Vol. 2 269 (1996)

[2]W. Cai, B. B. Das, F. Liu, M. Zevallos, M. Lax, R. R. Alfano, ''Time Resolved Optical Diffusion Tomographic Image Reconstruction in Highly Scattering Turbid Media'' Proceedings of National Academy of Sciences USA, Vol 93, 13561 (1996)

[3]W. Cai, B. Luo, M. Lax, B. B. Das, F. Liu, R. R. Alfano, ''Impurity Detection in Turbid Media by Diffusion Tomography'' Proceedings of the 1996 Scientific Conference on Obscuration and Aerosol Research, Aberdeen Proving Ground (1996)

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Tomography and Spectroscopy of Tissue III, SPIE 3597, p2-4 (1999).

[15]W. Cai, S. K. Gayen, M. Xu, M. Zevallos, M. Alrubaiee, M. Lax, R. R. Alfano, "Optical tomographic image reconstruction from ultrafast time-sliced transmission measurements" Applied Optics Vol. 38 p4237-4246 (1999).

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Patents

[1]R. R. Alfano, W. Cai, F. Liu, M. Lax, B. B. Das, ''Time-resolved Diffusion Tomographic Image Reconstruction of Highly Scattering Turbid Media -- Breast Brain and Human Body'' U.S. Patent 5,813,988, issued Sep. 29, 1998.

[2]R. R. Alfano, W. Cai, F. Liu, M. Lax, B. B. Das, ''Time-resolved Diffusion Tomographic 2D and 3D Imaging in Highly Scattering Turbid Media'' U.S. Patent 5,931,789, issued Aug. 3, 1999.

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The following people have received at least partial support from this grant.

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